

DISCOVERY OF A NEUTRON STAR OSCILLATION MODE DURING A SUPERBURST

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Abstract

Neutron stars are among the most compact objects in the universe and provide a unique laboratory for the study of cold ultra-dense matter. While asteroseismology can provide a powerful probe of the interiors of stars, for example, helioseismology has provided unprecedented insights about the interior of the sun, comparable capabilities for neutron star seismology have not yet been achieved. Here we report the discovery of a coherent X-ray modulation from the neutron star 4U 1636–536 during the February 22, 2001 thermonuclear superburst seen with NASA's *Rossi X-ray Timing Explorer* (RXTE) that is very likely produced by a global oscillation mode. The observed frequency is 835.6440 ± 0.0002 Hz (1.43546 times the stellar spin frequency of 582.14323 Hz) and the modulation is well described by a sinusoid ($A + B \sin(\phi - \phi_0)$) with fractional half-amplitude of $B/A = 0.19 \pm 0.04\%$ (4–15 keV). The observed frequency is consistent with the expected inertial frame frequency of a rotationally-modified surface g-mode, an interfacial mode in the ocean-crust interface or perhaps an r-mode. Observing an inertial frame frequency—as opposed to a co-rotating frame frequency—appears consistent with the superburst's thermal emission arising from the entire surface of the neutron star, and the mode may become visible by perturbing the local surface temperature. We briefly discuss the implications of the mode detection for the neutron star's projected velocity and mass. Our results provide further strong evidence that global oscillation modes can produce observable modulations in the X-ray flux from neutron stars.

Subject headings: stars: neutron — stars: oscillations — stars: rotation — X-rays: binaries — X-rays: individual (4U 1636–536) — methods: data analysis

1. INTRODUCTION

Neutron stars provide natural laboratories for the study of ultra-dense matter. A primary method for such studies is to accurately measure the mass-radius relationship for neutron stars, which depends directly on the equation of state of dense matter. However, different phases of ultra-dense matter can have similar equations of state, such that mass-radius measurements alone may not be definitive in probing the composition of matter at the highest densities (Alford et al. 2013; Lattimer 2012). Additional, complementary observables sensitive to the phase of dense matter would be extremely valuable for a more comprehensive understanding of neutron star interiors. The frequencies and damping timescales of different global oscillation modes of neutron stars, such as the Rossby waves (r-modes) and gravity modes (g-modes), which have the Coriolis force and buoyancy as their respective restoring forces, depend on their interior structure and composition (Yoshida & Lee 2000; Alford et al. 2012). Thus, observations of the oscillation modes of a neutron star can, in principle, provide such a complementary probe of its interior properties (Passamonti & Andersson 2011).

The low mass X-ray binary (LMXB) 4U 1636–536 (hereafter, 4U1636) is a well studied accreting neutron star binary with an optically-determined orbital period of 3.8 hr, and is also a well-known X-ray burst source (Augusteijn et al. 1998; Giles et al. 2002). Oscillations at ≈ 582 Hz are detected during some of its thermonuclear bursts and are almost certainly spin modulation

pulsations (Strohmayer et al. 1998). This conclusion is further supported by the detection of 582 Hz pulsations during a portion of the thermonuclear superburst observed from this source on 22 February, 2001 with the Proportional Counter Array (PCA) onboard RXTE (Strohmayer & Markwardt 2002). Superbursts are rare, energetic X-ray flares observed from LMXBs that are likely caused by unstable thermonuclear burning of a carbon-rich layer formed from the ashes of normal Type I X-ray bursts. The time evolution of the 582 Hz pulsations during the superburst was entirely consistent with the system's known orbital ephemeris, and modeling of the frequency drift enabled some constraints on the neutron star's projected orbital velocity and its rest-frame spin frequency (Strohmayer & Markwardt 2002; Casares et al. 2006).

The bright, hours-long superburst from 4U1636 provides a unique opportunity to search for X-ray modulations produced by global neutron star oscillation modes for several reasons. First, the combination of its high luminosity (and thus high counting rate in the PCA) and long duration provides excellent sensitivity to potentially weak modulations. Second, the neutron star orbit constraint derived from the 582 Hz pulsations enables a coherent search by removal of the phase delays due to the neutron star's orbital motion (Strohmayer & Mahmoodifar 2014). Finally, the thermonuclear burning provides a plausible mechanism for the excitation of modes (the so-called ϵ -mechanism), and the shock wave produced by detonation of the carbon fuel which powers the superburst is also likely to excite wave motions at or near the

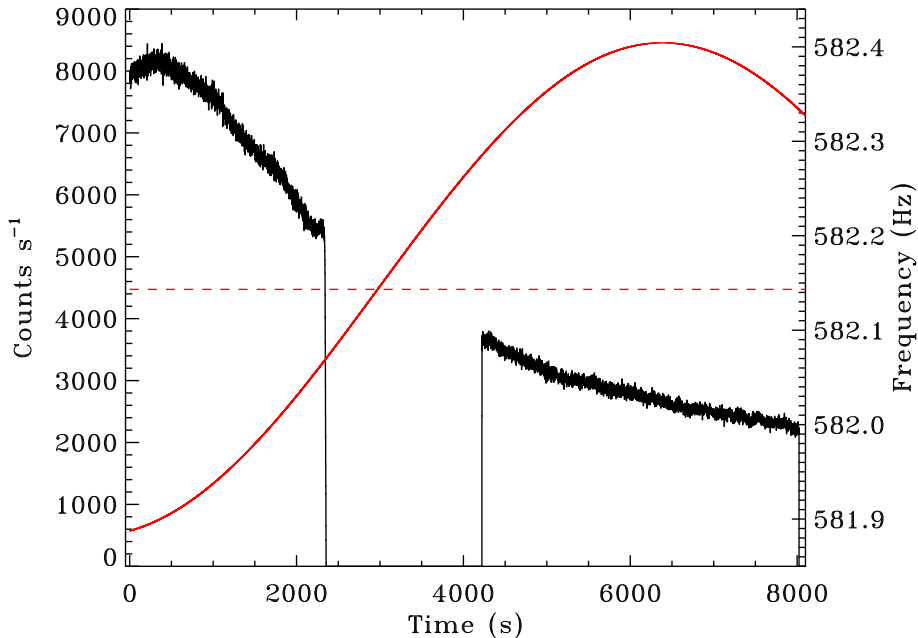


FIG. 1.— Light curve of the portion of the superburst from 4U1636 used in our pulsation search, along with the frequency evolution from our best-fitting orbit model (red curve, right axis). The data are the 4 – 15 keV PCA count rates (left axis) in 1 s bins. The gap in the range from $\approx 2500 - 4000$ s results from Earth occultation of the RXTE satellite. The first data interval begins just prior to the peak of the superburst. Time zero is MJD 51962.70863263 (referred to the TDB timescale).

surface (McDermott & Taam 1987; Strohmayer & Lee 1996; Piro & Bildsten 2004; Keek et al. 2012).

2. A COHERENT MODE SEARCH DURING THE SUPERBURST

We carried out a coherent pulsation search during the superburst in the manner described in detail in Strohmayer & Mahmoodifar (2014). As the methods are clearly described there we omit some of the details here. We used the high time resolution event mode (E_125us.64M.0.1s) data obtained for most of the first two RXTE orbits in which the superburst was observed (see Strohmayer & Markwardt 2002 for a discussion of the PCA data obtained during the superburst). For the orbit correction we began with the values that minimized a χ^2 fit to the phase timing residuals of the 582 Hz pulsation, but with the orbit period fixed at the well-known value of 0.15804693(16) days (Strohmayer & Markwardt 2002; Giles et al. 2002). This gave a pulsar frequency of 582.14323 Hz, a projected neutron star velocity of 134.53 km/s, and an epoch of $T_{90} = 51962.74302977$ MJD (referred to Barycentric Dynamical Time, TDB). These values are all consistent with those reported by Strohmayer & Markwardt (2002). After correcting the event times for the neutron star’s orbital motion, we created light curves sampled at 4096 Hz spanning 8000 s of the portions of the first two RXTE orbits with high time resolution data (see Figure 1 in Strohmayer & Markwardt 2002). We generated light curves in four energy bands, beginning with the full PCA band, and then restricted the range to more closely match that of the superburst’s thermal emission component (Keek et al. 2014). Our last and tightest energy range spans $\approx 4 - 15$ keV, where most of the detected superburst thermal emission falls. This light curve re-sampled to 1 second bins is shown in

Figure 1 along with the orbital frequency model used to correct the event times (red curve).

We then computed power spectra and searched the same frequency ranges as described in Strohmayer & Mahmoodifar (2014). These encompass the expected range of frequencies—relative to the stellar spin frequency—for r-modes and some rotationally modified g-modes, if a mode modulates neutron star emission at either the mode’s co-rotating ($0.4166 < \sigma/\Omega < 0.7567$) or inertial frame frequency ($1.243 < \sigma/\Omega < 1.583$). Here, σ is a Fourier frequency and Ω is the stellar spin frequency. We note that for the superburst’s thermal emission component—which almost certainly reflects emission from the whole surface of the neutron star—it would seem the inertial frame frequencies are the more likely to be observed (Heyl 2005; Lee & Strohmayer 2005). This is in contrast to the case of thermal emission from the hot-spot of an accreting millisecond X-ray pulsar (AMXP), where the mode can periodically perturb the shape of the hot-spot that is fixed in the rotating frame, producing an observed modulation at the mode’s co-rotating frame frequency (Numata & Lee 2010).

Our analysis revealed a significant power spectral peak at a frequency of 835.644 Hz ($\sigma/\Omega = 1.43546$), in the inertial frame frequency search range. The peak has a Leahy-normalized power of 49.3, and we estimate its significance as $\exp(-49.3/2) \times N_{\text{trials}}$, where $N_{\text{trials}} = 4 \times 3.17 \times 10^6$ is the total number of Fourier frequency bins in the two ranges searched. The factor of 4 conservatively accounts for the number of energy channel ranges we used to compute light curves and power spectra, and results in a significance of 2.5×10^{-4} . The estimate is conservative because the channel ranges searched were not all independent. We also carried out extensive

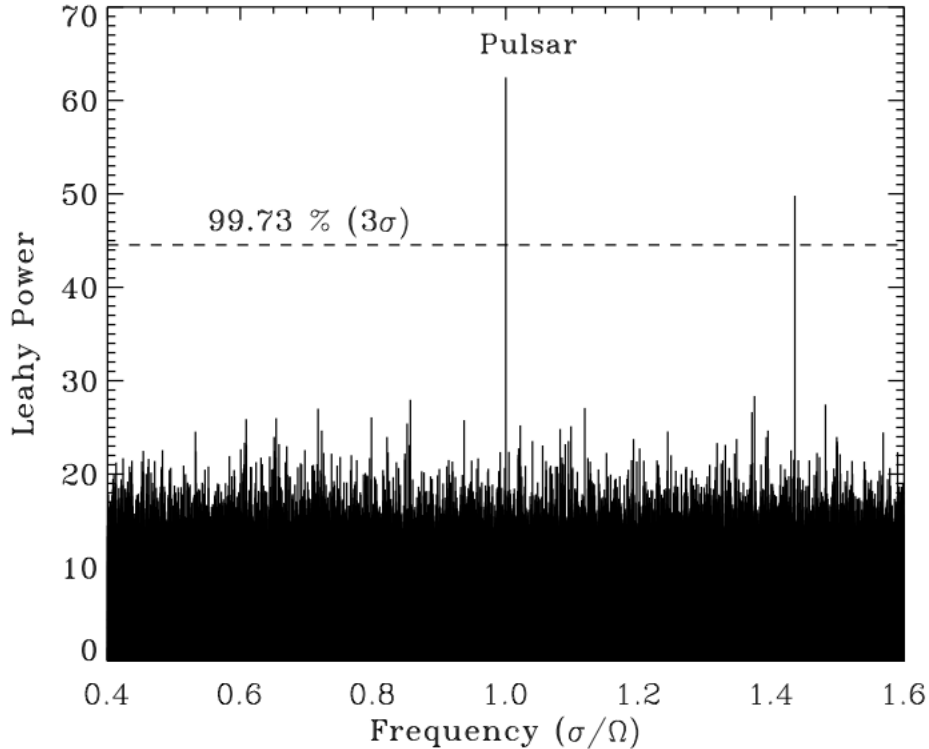


FIG. 2.— A portion of the power spectrum (Leahy-normalized) computed from the 8000 s superburst interval shown in Figure 1. The x-axis shows Fourier frequency scaled by the pulsar spin frequency. The plotted range includes both the co-rotating ($0.4166 \leq \sigma/\Omega \leq 0.7567$) and inertial ($1.243 \leq \sigma/\Omega \leq 1.583$) frame frequency ranges searched. The pulsar signal appears at 1 in these units (labeled), and the oscillation mode peak is evident near 1.43546, with a Leahy power close to 50. The dashed horizontal line denotes the 3σ detection level assuming a number of trials equal to $4 \times 3.17 \times 10^6$. The factor of 4 conservatively accounts for the number of energy ranges searched.

Monte Carlo simulations to assess the significance, taking into account the non-independence of the energy channel ranges searched. From these simulations we find a significance of $\approx 1.5 \times 10^{-4}$, which gives us additional confidence in the detection. Figure 2 shows a portion of the full power spectrum ($0.4 \leq \sigma/\Omega \leq 1.6$) which includes the two frequency ranges searched, as well as the range around the known pulsar frequency. There are clearly two significant peaks present in the power spectrum, one is the known pulsar signal (at 1 in these units), and the other is the putative oscillation mode frequency at 1.43546. There are no other significant peaks detected. As a further check, we used the Fourier frequency bins above $\sigma/\Omega = 1.6$ to investigate the noise power distribution, and find that it closely matches the expected $\exp(-P/2)$ distribution, giving us further confidence that our significance estimates are robust.

The 835 Hz signal we detect is consistent with a coherent oscillation over the 8000 s of the light curve. We emphasize that prior searches, such as those which discovered the 582 Hz pulsations, would not have detected this modulation because they did not account for the motion of the neutron star, which smears a narrow band signal into many adjacent Fourier frequency bins. An estimate of this effect can be gleaned from Figure 1. The full (peak to trough) fractional change in the frequency due to the orbital motion is $\Delta\nu/\nu \approx 0.5/582 = 8.6 \times 10^{-4}$. A coherent (single bin) signal at 835 Hz will be smeared into $N_f = 835 \times (\Delta\nu/\nu)/\delta f$ bins, where δf is just the frequency resolution of the power spectrum, in this case

$\delta f = 1/8000$ s, and $N_f = 835 \times (0.5/582) \times 8000 \approx 5700$. Any such signal would be swamped by the poisson noise in this large number of Fourier bins (Wood et al. 1991).

We folded the light curve data (4 – 15 keV) at the detected frequency and fit a sinusoidal model of the form $A + B \sin(\phi - \phi_0)$ to the resulting profile (see Figure 3). This model provides an excellent fit to the data, and we find a fractional half-amplitude of $B/A = 0.19 \pm 0.04\%$. We do not find any evidence for significant harmonics associated with this signal. Assuming the observed frequency is the inertial frame frequency of an oscillation mode ($\omega_i/\Omega = 1.43546$), we can convert it to a co-rotating frame frequency if we know its azimuthal wavenumber, m , since the two frequencies are related as $\omega_i = m\Omega - \omega$. Interestingly, for $m = 2$ we find that $\omega/\Omega = 2 - 1.43546 = 0.56454$, which is close to the candidate frequency ratio of 0.57276 we identified in the AMXP XTE J1751–305 (Strohmayer & Mahmoodifar 2014), suggesting that the frequencies identified in the two sources could perhaps be associated with the same oscillation mode. For the AMXP source the modulation mechanism is more likely due to oscillation-induced perturbations to the hot-spot fixed in the rotating frame, whereas for the superburst, emission from the entire surface can be modulated by a mode, perhaps due to local variations in the surface temperature. As mentioned above, these processes would naturally lead to modulations at the co-rotating and inertial frame frequencies, respectively.

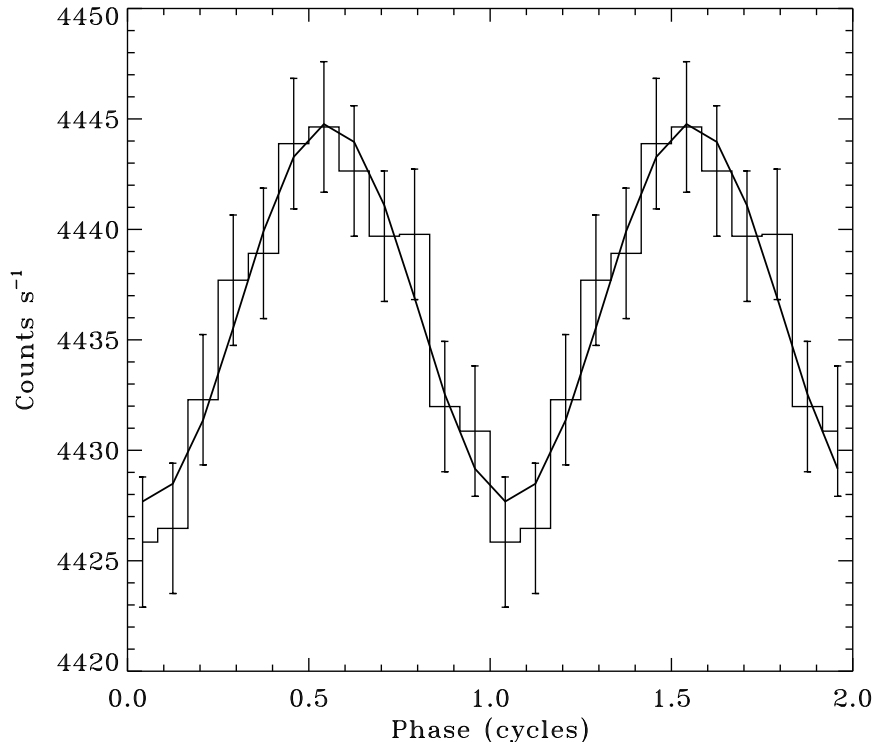


FIG. 3.— Pulse profile in the $\approx 4\text{--}15$ keV band obtained by folding the light curve data at the oscillation mode frequency of $\sigma/\Omega = 1.43546$ in 12 phase bins. Two cycles are plotted for clarity. The best fitting sinusoidal model (solid curve), $A + B \sin(\phi - \phi_0)$, is also plotted. The fractional half-amplitude of the best fitting model is $B/A = 0.19 \pm 0.04\%$.

3. DISCUSSION

Recent theoretical work has shown that the mode frequency ratio relative to the spin frequency indicated for J1751–305 is consistent, in principle, with the $l = m = 2$ r-mode for neutron stars with plausible masses and radii (Andersson et al. 2014), and surface g-modes with $l = 1$ or 2 (Strohmayer & Mahmoodifar 2014). To the extent that an $m = 2$ r-mode identification is appropriate for the modulation during the superburst, and since the mode frequency ratios are similar, the same r-mode identification appears possible for 4U1636 as well. The $l = m = 2$ r-mode is the most unstable to the emission of gravitational waves and its amplitude can grow exponentially—potentially causing a rapid spin-down of the star—if viscosity and other non-linear dissipation processes are not strong enough (Andersson 1998; Lindblom et al. 1998; Owen et al. 1998). The amplitude of the r-modes determines how fast they can spin down the star. Now, the r-mode amplitude likely required to account for the observed X-ray modulation during the superburst would, if continuously present, produce a strong spin-down of the star (Andersson et al. 2014; Strohmayer & Mahmoodifar 2014). Such a spin-down is inconsistent with the pulse timing data for J1751–305 (Strohmayer & Mahmoodifar 2014; Andersson et al. 2014), but we note that there are no comparable long term spin-down measurements for 4U1636, as the source has never been detected as a persistent pulsar. Excitation of the mode to an observable amplitude might also be intermittent, perhaps driven by the superburst’s energy release.

However, these inferences do not take account of the presence of a solid crust within the neutron star. It has recently been argued that the r-mode amplitude may be “amplified” in the surface layers above the crust compared to the core because the crust can isolate the surface layers from the core motions (Lee 2014). Indeed, recent estimates of r-mode amplitudes—at least those in the core—suggest a low saturation amplitude of $10^{-7} - 10^{-8}$ (Haskell et al. 2012; Mahmoodifar & Strohmayer 2013). Amplification of the mode in the surface layers might then account for the observed X-ray modulations, and if some process limits the r-mode saturation amplitude in the core (Bondarescu & Wasserman 2013), then the apparent inconsistency with the long-term spin evolution in J1751–305 could perhaps be mitigated. Alternatively, surface g-mode or ocean-crust interface mode identifications remain viable, and we note that rotational “squeezing” of the mode displacements toward the rotational equator does not necessarily pose a problem for the visibility of the mode in either of these cases, as the superburst involves emission from the entire neutron star surface, and not from a hot-spot localized near the rotational pole (Bildsten et al. 1996; Piro & Bildsten 2005).

If the putative inertial frame frequency at $\omega_i/\Omega = 1.43546$ is indeed constant over the 8000 s light curve interval, then it suggests that the neutron star velocity can be much more tightly constrained than indicated by the time evolution of the 582 Hz pulsations alone (Strohmayer & Markwardt 2002; Casares et al. 2006). That is because the 582 Hz pulsations were detected over

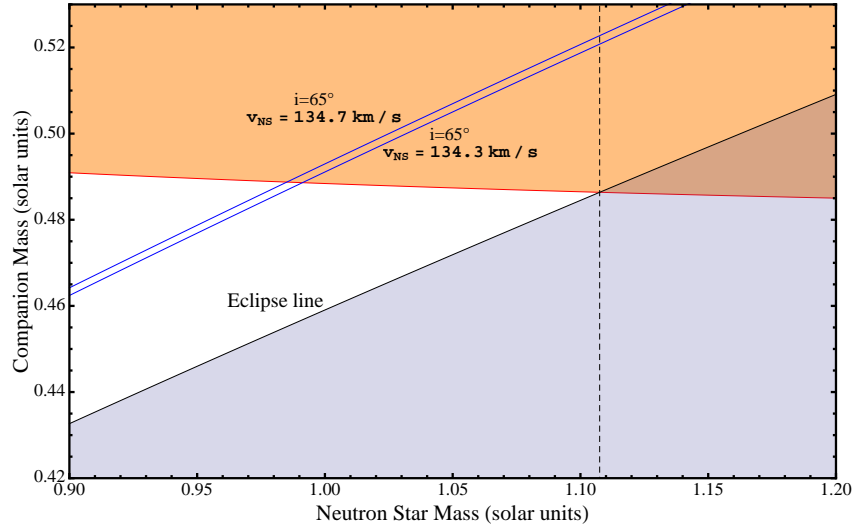


FIG. 4.— Constraints on the component masses of 4U1636 assuming the neutron star velocity of 134.5 ± 0.2 km/s suggested by our mode frequency detection. The orange region is excluded as zero age main sequence (ZAMS) stars above this limit will have radii larger than the Roche lobe radius for 4U1636. The blue region below the “eclipse line” is excluded as these systems would not be able to satisfy the velocity constraint (taken as $v_{ns} \geq 134.3$ km/s) at an inclination angle which would preclude eclipses. The maximum allowed mass under these assumptions is $M_{ns} \leq 1.108M_{\odot}$, and is marked by the vertical dashed line. The region of allowed masses for a system inclination angle of $i = 65^{\circ}$ (inside the parallel blue lines) is also shown, to indicate the precision which could be attained if both the inclination and velocity were accurately known.

a much shorter fraction of the orbital period (800 s) than the 8000 s detection interval of the 835 Hz modulation. The much shorter pulse train of the 582 Hz oscillation was consistent with a much larger range of neutron star orbital velocity (90 – 175 km/s) than the 835 Hz signal (Strohmayer & Markwardt 2002). Indeed, varying the orbital parameters away from the values for which the 835.644 Hz signal was detected results in a “smearing-out” of the signal peak. As noted toward the end of §2, this is the expected behavior of a coherent modulation when the chosen orbital parameters do not accurately match the “true” values.

Assuming the mode frequency is constant in the star’s frame, and using it as a “matched filter,” we can, in principle, constrain the projected neutron star velocity to 134.5 ± 0.2 km/s. A velocity outside of this range results in significant signal loss in the 835.644 Hz oscillation. We caution, however, that this is a somewhat indirect means to infer the star’s velocity because we do not have independent verification that the mode frequency is constant in the star’s frame. For example, some intrinsic variation of the mode frequency could mean that the orbital velocity which maximizes the 835 Hz signal is different from the true orbital velocity. Previous radial velocity studies of 4U1636 based on both optical spectroscopy and the 582 Hz superburst pulsations suggested a lower projected neutron star velocity, in the range from 90 – 113 km/s. This was based on a “spectroscopic ephemeris” for the epoch (phase) of superior conjunction of the companion deduced from Doppler tomography of the Bowen emission lines observed from the optical companion (V801 Ara; Casares et al. 2006). The offset in the “spectroscopic” and “photometric” phases (used here in our 835.643 Hz signal detection) corresponds to $\approx 2.5\sigma$ of the statistical uncertainty given for the reference epoch of the spectroscopic ephemeris (Casares et al. 2006), however,

the inclusion of systematic uncertainties associated with identifying accurately the site of Bowen fluorescence in the binary, as well as the (smaller) uncertainty in the orbital period, would further reduce this potential discrepancy. We also note that the timing analyses of the 582 Hz pulsations modestly favor—in yielding lower χ^2 timing residuals—the higher neutron star velocity suggested by our 835.643 Hz oscillation detection (Strohmayer & Markwardt 2002).

Nevertheless, such a high neutron star velocity would have important implications for its mass, as we now explain. Constraints on the component masses of 4U1636 assuming a neutron star velocity of 134.5 ± 0.2 km/s are shown in Figure 4. Systems within the orange shaded region are disfavored as any zero age main sequence star (ZAMS) is larger than the Roche lobe radius for 4U1636. We used a standard estimate for the radius of the Roche lobe (Eggleton 1983) and the stellar mass-radius relation of Tout et al. (1996) to determine the lower boundary of this region. The “eclipse line” denotes systems which give a neutron star velocity equal to the 1σ lower bound of 134.3 km/s at an inclination angle for which eclipses just begin. Since eclipses are not seen from 4U1636, the parameter space below this line is excluded. We used Kepler’s law and solved the Roche lobe eclipse geometry for a point source (Chanan et al. 1976) to draw this line. The allowed range of masses is also shown if the system inclination were $i = 65^{\circ}$ (within the parallel blue lines), and is meant to suggest the accuracy that could be achieved if both the velocity and inclination were well constrained. The vertical dotted line marks the maximum neutron star mass under these assumptions, $M_{ns} \leq 1.108M_{\odot}$. From Figure 4 it is evident that an orbital velocity as high as 134.5 ± 0.2 km/s would strongly favor a low mass neutron star in 4U1636. Interestingly, there is growing evidence for “light” neutron stars, including the X-ray bi-

naries 4U 1538–52 and SMC X-1 (Rawls et al. 2011; Coe et al. 2013). As discussed by Lattimer (2012), the physics of core-collapse and the thermodynamics of the resulting lepton-rich proto-neutron star, suggests a minimum mass of about $0.9 - 1.1 M_{\odot}$ depending on the entropy profile of the star (Strobel et al. 1999). Thus, accurate measurements near the minimum would provide important insights into the core-collapse physics (Lattimer 2012). Finally, we emphasize that an independent confirmation of the neutron star’s orbital velocity is crucial to definitively establish such a low mass for 4U1636.

4. SUMMARY AND CONCLUSIONS

We carried out a search for high frequency coherent X-ray modulations during the February 2001 superburst from the LMXB 4U 1636–536 observed with RXTE. We used a circular orbit model deduced from the time evolution of the 582 Hz pulsations seen previously during the superburst to remove the Doppler delays due to binary motion of the neutron star. We detected a coher-

ent modulation at a frequency of 835.6440 ± 0.0002 Hz (1.43546 times the stellar spin frequency of 582.14323 Hz), with a significance estimated from Monte Carlo simulations of $\approx 1.5 \times 10^{-4}$, and a fractional half-amplitude of $0.19 \pm 0.04\%$. This frequency is consistent, in principle, with the expected inertial frame frequency of an $l = m = 2$ r-mode, a rotationally modified surface g-mode, or an ocean-crust interfacial mode. Our results provide further strong evidence that global oscillation modes can produce observable modulations in the X-ray flux from neutron stars. Sensitive searches for such signals should be a priority for future, large area X-ray timing missions.

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